Color Reproduction of a Multiband 3D Projector

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Abstract Stereoscopic video technology, which enables three-dimensional (3D) images to be displayed, has been developing rapidly. However, existing devices are unable to achieve accurate color reproduction. This paper proposes a method to accurately reproduce the colors displayed by a multiband 3D projector. Previously, we proposed a stereoscopic display system with an expanded color gamut. However, we only confirmed the expansion of the color gamut of the proposed system and were unable to display stereoscopic images with accurate colors. We now propose an accurate color and spectral reproduction method for a stereoscopic image display system for which we developed an expanded color gamut by means of the covariance matrix adaptation evolution strategy (CMA-ES). The system design for optimizing the color reproduction of the multiband 3D projector is described. An experimental evaluation of the color reproducibility showed the performance of the proposed method to be superior to that of an existing method.

Key words: 3D image, Color reproduction, Stereo spectral image, Multiband projector, System optimization, CMA-ES.

1. Introduction

In recent years, stereoscopic image technology has improved and devices capable of displaying three-dimensional images are becoming inexpensive. However, devices that display stereoscopic images cannot reproduce colors accurately because these colors are reproduced by using combinations of the three primary RGB colors. Three-dimensional imaging devices with the ability to display colors accurately could be used in various fields such as online shopping, remote medical care, and electronic museums.

There are two important requirements for accurate color reproduction. The first is to use a spectral image as input data and the other is to ensure that the display has a wide color gamut. A spectral image is an image in which each pixel contains spectral information and can be used to record and reproduce color more accurately than an RGB color image. Several previous studies have been concerned with the acquisition of spectral images. A method using a multiband camera123 and a method using a DLP projector and a high-speed camera4 have been proposed. More accurate color reproduction is considered to be possible by using a spectral image as input and processing the spectral information. However, conventional display devices are unable to reproduce color accurately because they do not have the necessary color gamut. Yagamuchi et al. developed a projection display system based on six primary colors5. However, this system has a complex mechanism, and it is very expensive; thus, a more simple system is required. On the other hand, few previous studies of display systems that can process both stereoscopic and spectral images at the same instant have been reported.

Our previous work involved the development of a stereoscopic image system with an expanded color gamut6, and this work described the decision policy of the combination of the two notch filters. This is a simple system that uses two general 3D projectors and notch filters. Assuming that stereo spectral images are input into the system, it enables target colors to be reproduced more accurately. However, in the above-mentioned study we only confirmed the expansion of the color gamut of the proposed system and were not yet able to display three-dimensional images in accurate color. Accurate color reproduction would necessitate determination of the multi-primary color signal values. This paper proposes a method to determine multi-primary color signal values and display stereoscopic images in accurate color by using a spectral image as input.

2. Related work

When a stereo spectral image is used as input into our system, it requires the spectral information to be decomposed into multi-primary color signal values. Several methods capable of performing this decomposition
into multi-primary color signal values have already been proposed. There are mainly two types of methods. One is the colorimetric color reproduction technique and the other is spectral color reproduction. The former relies on the matrix-switching method proposed by Ajito et al.\textsuperscript{7} and the LIQUID method\textsuperscript{8} proposed by Motomura et al. These methods affect the reproduction of color if the observer’s color matching function does not match that of the standard observer. The latter type of method involves an optimization based on a Lagrange multiplier\textsuperscript{9} proposed by Murakami et al. Unlike the colorimetric color reproduction method, the latter method makes it possible to reproduce colors by considering the individual differences of the color matching function. When a spectral image is input into the system, the output color should be the result of spectral color reproduction because each pixel of the spectral image contains spectral information. However the Lagrange method often outputs the calculation result beyond the value that a system can take such as negative values. So to solve this problem, we propose the method using covariance matrix adaptation evolution strategy (CMA-ES).

3. Signal value determination

The method proposed in this paper enables accurate color and spectral reproduction by using a stereo spectral image to project the multi-primary colors in more than three RGB bands. The system is outlined in the first part of this section. Next, a method for multi-primary color signal value determination using the covariance matrix adaptation evolution strategy (CMA-ES)\textsuperscript{10,11}, which is a type of optimization method, is described.

Evolution strategy is widely used in the real numerical optimization, and it is a technique that mimics the evolution of organisms. Roughly speaking, there are two methods in the evolution strategy. One is a technique to transition from one state to another state which is called (1 + 1)-ES, and the other is a technique to transition from more than one state to others states which is called \( (\mu, \lambda) \)-ES. Search technique is used mainly mutation. Mutation is determined based on statistics. CMA-ES\textsuperscript{10,11} is the typical method of evolution strategy. CMA-ES advances the search by updating the covariance matrix and mean vector as statistic of multivariate normal distribution. In CMA-ES, it is necessary to set a number of parent populations \( \lambda \) and a number of descendants \( \mu \).

3.1 Multiband 3D projector

This section presents an outline of the system used in this study. Figure 1 shows an overview of the system in which two 3D projectors equipped with different optical filters is used. The system uses two notch filters to change the RGB spectral characteristics to six-band color information. Figure 2 shows the six primary colors that are generated. A stereoscopic image is displayed on the screen by using the two projectors to achieve a synchronous presentation. The color gamut of our system is shown in Fig. 3. The color spectra we want to display are reproduced by using the information of the six color bands.

3.2 Overview of signal value determination

The process of determining the multi-primary color signal values comprises two steps. In the first step, two pairs of XYZ values corresponding to each projector space are obtained from the spectral information
and the second step entails obtaining the signal values from the XYZ values. These steps are named the color conversion step and display characteristic step, respectively. The color conversion in each step is determined using CMA-ES. The following subsection describes the design for the optimization of the aforementioned two steps.

3.3 Color conversion

Two sets of XYZ values are obtained from the spectral information in the color conversion step. First, the inputted spectral information is converted into six signal values in order to add an evaluation about the spectrum during optimization. Then, the XYZ values in the color space of each projector are obtained using the six signal values, the primary color characteristics, and the xyz color matching function.

A fitness function for the simultaneous optimization of the spectrum and color was developed. Figure 4 shows the outline of the design. Let the spectral information sampled at 10-nm intervals from 380 nm to 740 nm be the training data \( S \), which can be expressed as follows:

\[
S = \begin{bmatrix} s_{380} & s_{390} & \ldots & s_{740} \end{bmatrix}^T
\]  

(1)

Further, let the transformation matrix be \( T(6 \times 37) \), and signal value be \( C \), in which case the conversion is given by equation 2.

\[
C = TS
\]  

(2)

With regard to the spectrum, the fitness value is the square error between the spectrum of training data and the spectrum corresponding to the signal values of the system output, which is multiplied by the transformation matrix. Specifically, the spectral distribution \( S' \) that is reproduced by the system can be expressed as the following equation 3:

\[
S' = PC
\]  

(3)

where \( P \) is the primary color spectrum of each maximum output of the system. Let the elements of \( S' \) be \( s'_\lambda \). The spectral fitness value \( F_s \) is calculated by using equation 4.

\[
F_s = \sum_\lambda (s_\lambda - s'_\lambda)^2
\]  

(4)

With regard to color, each of the XYZ tristimulus values are calculated from the spectrum of training data and the spectrum that is reproduced by the system. Then, the tristimulus values are converted to \( Y_{xy} \), which is the relative value, as equation 5.

\[
Y = Y, x = \frac{X}{X + Y + Z}, y = \frac{Y}{X + Y + Z}
\]  

(5)

The square error of the \( Y_{xy} \) values is used as the color fitness value. Namely, the color fitness value \( F_c \) is calculated using the following equation 6:

\[
F_c = (Y - Y')^2 + (x - x')^2 + (y - y')^2,
\]  

(6)

where \( Y, x, \) and \( y \) are calculated from the spectrum of training data and \( Y', x', \) and \( y' \) are calculated from the spectrum that is reproduced by the system.

From equation 4 and 6, the fitness value \( F \) of the fitness function is calculated as follows:

\[
F = \frac{w_1}{37} F_s + \frac{w_2}{3} F_c,
\]  

(7)

where \( w_1 \) and \( w_2 \) are an arbitrary weighting factor respectively. All elements are normalized.

If the spectral reproduction is important, \( w_1 \) is set larger than \( w_2 \). The dependence degree of fitness value can be changed by adjusting both weights.

The signal value should be within the range the system can display. Thus, a penalty is given when the signal value is out of range. Optimization proceeds until \( F \) is minimized. Finally, the transformation matrix \( T \) that minimizes \( F \) is selected.

3.4 Display characteristics

A fitness function was designed for the display characteristics. The design had to consider that the relation between the input and output of the projector is not linear because the projector usually has display characteristics. In addition, a physical model related to general display characteristics cannot be used because a multiband 3D projector is composed of DLP projectors. The used projector in the system has 6 segment color wheel i.e. Red, Green, Blue, Yellow, Cyan and White (transparency) in order to enhance brightness and color reproduction\(^2\). The gamma correction using only R, G and B cannot reproduce correct color, so we add the cross terms, i.e. RG, GB, BR and RGB in order to obtain correct color reproduction. Therefore, the display model representing the relationship between the input...
and the output is assumed by using the following equation 8, and the transformation matrix and gamma value are optimized using CMA-ES.

\[
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix}
= T
\begin{bmatrix}
R^*G^*B^* \\
(RG)^* \\
(GB)^* \\
(BR)^* \\
(RGB)^*
\end{bmatrix}
\]  

where \( T \) is the transformation matrix of \( 3 \times 7 \). The fitness function is designed such that these values are obtained by optimization. Figure 5 shows the outline of the design. The fitness value \( F_p \) is the square error between the \( L^*a^*b^* \) values of the XYZ values converted by the display model and the \( L^*a^*b^* \) values of the color measured from the projector. Therefore, when \( L^*a^*b^* \) of the values converted by the display model is \( L^*_1a^*_1b^*_1 \) and \( L^*a^*b^* \) of the measured values is \( L^*_2a^*_2b^*_2 \), \( F_p \) can be expressed as follows:

\[
F_p = (L^*_1 - L^*_2)^2 + (a^*_1 - a^*_2)^2 + (b^*_1 - b^*_2)^2
\]  

During the optimization calculation, either one of gamma or the converted XYZ value may be negative depending on the generated transformation matrix. In such cases, penalties are given. The optimization proceeds until \( F_p \) becomes a minimum. Finally, the transformation matrix and the gamma value that minimizes \( F_p \) are determined as a display model. When the multi-primary signal values are actually obtained by the proposed method, reverse conversion of the display model is used.

3.5 Projection alignment

It is difficult to register the projected images of the two projectors manually. Therefore, the projected image of projector2 is adjusted to that of projector1 by using a camera. Specifically, this is achieved by projecting a checkerboard from each projector, a picture of each of which is then captured with a camera, respectively. The feature points are extracted from the captured images, after which the homography transformation matrix is calculated from the obtained feature points. When the images are projected, it is possible to adjust the projection position by applying the homography transformation to the image of projector2. In this regard, it is important to obtain a more optimal homography transformation matrix in order to perform a more accurate adjustment. The homography transformation matrix is improved by further applying similar processing from the adjusted projection position. High precision alignment can be realized by repeating this process several times.

4. Experiments

The projection experiments were carried out in a dark room. Two notch filters with different characteristics and two DLP projectors of the same type, namely the VIEW SONIC PJD6 Series, with a resolution of \( 1024 \times 768 \) were used to generate the six primary colors. A NVIDIA 3D Vision 2 wireless glasses kit was used to enable stereoscopic vision. Each projected image was registered by using a POINT GREY FL3-U3-32S2C-CS camera. The spectra and tristimulus values were obtained via a TOPCON SR3 spectroradiometer.

4.1 Primary color characteristics

The maximum intensity for the output of each primary color was measured. Figure 6 shows the relative intensity of each primary color. This graph shows that the intensity of G2 is especially weak. As a consequence, the optimization was performed in a space adjusted according to the intensity of G2.

4.2 Optimization setting

Regarding the color conversion step, the spectral reflectance of 1269 Munsell colors and 10 achromatic data of which the spectral reflectance were all constant \((0.1,0.2,\ldots,1.0)\) were used as training data. The light
source assumed a D65 light source. In the CMA-ES, for \( n \) obtained parameters, the number of parent populations \( \lambda \) was \( \lambda = 4 + \lceil 3\ln(n) \rceil \), the number of descendants \( \mu \) was \( \mu = \lfloor \lambda/2 \rfloor \), and the initial step size \( \sigma \), which is the parameter indicating the size of the initial mutation, was \( \sigma = 0.02 \). Optimization was continued for 20,000 iterations. From Figure 6, our prototype system is difficult to reproduce correct spectral information since the spectral characteristics of G2 is much smaller than others. So we focus on the reproduction of XYZ color. Therefore, as for the fitness function, the weighting factors were set to \( w_1 : w_2 = 1 : 10 \) by the result of preliminary experiment. When the signal value is out of range, a constant value of 100 is assigned as the penalty. Furthermore, the fitness value of the achromatic data was weighted 10 times because the number of achromatic data points is smaller than the number of Munsell colors (chromatic data).

Regarding the display characteristic step, \( 7 \times 7 \times 7 = 343 \) data points, which are the signal values (10,50, \cdots, 250) of each of the RGB channels were used as the training data. The same settings were used for CMA-ES as for the color conversion process. Optimization was continued for 3,000 iterations. As for the fitness function, when the gamma value became negative, a fixed value of 10,000 was assigned as a penalty value. When the XYZ value became negative, the fitness value was weighted 10 times.

4.3 Evaluation of color reproduction

The reproduction of color was evaluated by verifying the conversion accuracy optimized by the proposed method. The spectral reflectance of the X-rite Color Checker CLASSIC \(^{14}\) in combination with a D65 light source was used as the input data for the verification test. The proposed method was compared with the results obtained in previous work, which involved an optimization method based on a Lagrange multiplier. The color reproduction accuracy was evaluated by determining the \( L^*a^*b^* \) color difference between the theoretical value of the input data and the measured value. Figure 7 shows the evaluation result. The bar to the left of each patch number is the result of our method and the bar on the right is that of the Lagrange method. Table 1 lists the average, maximum, and minimum of \( L^*a^*b^* \) of the color difference of the test data.

Table 1  Average, maximum, and minimum of the \( L^*a^*b^* \) color difference

<table>
<thead>
<tr>
<th></th>
<th>Our method</th>
<th>Lagrange method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>4.35</td>
<td>9.37</td>
</tr>
<tr>
<td>Max</td>
<td>7.81</td>
<td>29.0</td>
</tr>
<tr>
<td>Min</td>
<td>1.63</td>
<td>2.36</td>
</tr>
</tbody>
</table>

4.4 Evaluation of spectral reproduction

The spectral reproduction accuracy was evaluated by calculating the RMSE of each set of test data in the range 400 nm to 700 nm. The results are shown in Figure 8. Table 2 shows the average, maximum, and minimum RMSE of the test data.

Table 2  Average, maximum, and minimum RMSE

<table>
<thead>
<tr>
<th></th>
<th>Our method</th>
<th>Lagrange method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>0.0708</td>
<td>0.0709</td>
</tr>
<tr>
<td>Max</td>
<td>0.191</td>
<td>0.191</td>
</tr>
<tr>
<td>Min</td>
<td>0.0104</td>
<td>0.0102</td>
</tr>
</tbody>
</table>

4.5 Projection of stereo spectral image

Two stereo images for each projector are obtained by inputting a stereo spectral image. The homography matrix obtained for alignment is applied to the stereo image of projector2. The images on the left and right as calculated by the proposed method are shown in Figure 9. Figure 10 shows the stereoscopic image that was obtained by superimposing the two stereo images. The resulting stereoscopic image produced with accurate color could be displayed and we can view it by wearing the 3D glasses.

5. Discussions

A method for accurate color and spectral reproduction of a stereoscopic image using two synchronized 3D projectors was proposed. The results that were obtained with the proposed method are superior to those obtained using the Lagrange method. However, compared with the Lagrange method, there was no significant difference in the colors. In Figure 8, the proposed method obtained almost the same result as the Lagrange method in terms of spectral reproduction. On the other hand, Figure 7 and Table 1 show that our
proposed method obtained better the results of color differences than the Lagrange method. It is for this reason that the accuracy of spectral reproduction of the proposed method becomes better than the Lagrange method at range of short wavelength for example Figure 8 (k), (n) and (p). It was shown that the proposed method can optimize the multiband 3D projector.

The spectral reproduction was very difficult to achieve accurately. As shown Figure 8, reproduction was particularly difficult to achieve around the 530-nm band. This is probably due to the primary color characteristics. To solve this problem, we need redesign of spectral characteristics of notch filters. On the other hand, we may be able to obtain the better spectral reproduction by adjusting the weights of the fitness function (equation 8). In this paper, the weights are fixed to $w_1 : w_2 = 1 : 10$. In next study, we try to find the most suitable weights for our prototype system.

In Figure 9, the images of the projector1 is reddish because the notch filter1 passes light of long wavelength, and the image of the projector2 is bluish because the notch filter2 passes light of short wavelength.

Stereo spectral images were displayed by multiband projection as shown Figure 10. The small amount of blurring indicates that superimposed projection can be performed with high accuracy. We can watch 3D images with expand color gamut using our prototype system. However, the projected image has a dark impression. This is because colors were reproduced in a space adjusted to the intensity of the G2 color. When a brighter image is required, optimization design considering brightness would be necessary.

The proposed method took about 5 seconds for calculating two transformation matrices i.e. the color con-
version and the display characteristics. However the processing time is not important since the two transformation matrices should be calculated only once before the use of the system.

6. Conclusions

This paper proposed a method for the accurate color and spectral reproduction of a stereoscopic image by multiband projection using two 3D projectors and two notch filters. Transformation matrices for the multi-primary color signal value determination were obtained using CMA-ES, which is a real numerical optimization technique and the conversion accuracy was verified. The proposed method produced more accurate results than an existing method. The proposed method also succeeded in displaying a stereoscopic image with accurate color. In future, we expect to display stereo spectral video by applying the method proposed in this paper.

References